Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 88 (2014) 69 – 76

Procedia Engineering

www.elsevier.com/locate/procedia

International Symposium on Dynamic Response and Failure of Composite Materials, DRaF2014

Response of Cylindrical Composite Structures to Underwater Impulsive Loading

S. Avachat, M. Zhou*

George W. Woodruff School of Mechanical Engineering
School of Materials Science and Engineering
Georgia Institute of Technology, Atlanta, GA, USA

Abstract

The response of cylindrical composite structures subjected to underwater impulsive loads is analyzed. The analysis focuses on the effect of varying structural attributes and material properties on load-carrying capacity, deflection, energy dissipation and damage. The structural designs studied are monolithic composite structures, and sandwich structures with foam cores of different relative densities and different radii. Underwater impulsive loads are generated using a novel experimental setup, and deflection and core compression are characterized using high-speed digital imaging. The experiments are supported by fully dynamic 3D numerical calculations which account for fluid-structure interactions and damage and failure mechanisms in the materials. For the same applied impulse, the monolithic cylindrical sections experience significant warping, delamination and cracking, while sandwich structures experience significantly lower damage. In sandwich structures, as the core density increases, the transmitted impulse and overall damage also increase. Deflection and warping in the impulsively loaded region are influenced by the radius of curvature and material orientation. Results show that cylindrical sandwich structures have superior blast-resistance than cylindrical monolithic structures of equal mass with only relatively minor increases in wall thickness. The experiments, computations and structure-performance relations offer approaches for improving the blast mitigation capabilities of cylindrical composite sections in critical parts of a ship structure like the keel, hull and pipes.

Peer-review under responsibility of the Organizing Committee of DRaF2014

Keywords: underwater impulsive loading, cylinderical structures, sandwich composites, fluid-structure interaction

* Corresponding author
E-mail address: min.zhou@me.gatech.edu

Peer-review under responsibility of the Organizing Committee of DRaF2014
doi:10.1016/j.proeng.2014.11.128

1. Introduction

Marine structures are designed to operate in hostile environments consisting of corrosive sea water, hot and cold temperature extremes, transient dynamic loads like hull slamming and complex three dimensional hydrodynamic loads. Additionally, naval structures are required to withstand weapons impacts and blast loads resulting from surface and underwater explosions. Recent assessments of marine structures have demonstrated that sandwich composites can provide good blast mitigation due to their high strength to weight ratios and high shear and bending resistances. Characterization of the behavior of composite materials and polymeric foams under impulsive loading is a prerequisite for the analysis and design of effective, blast resistant sandwich composites. Deformation and failure due to high rate loading in layered materials such as composite laminates has been the subject of numerous investigations in recent years. Gas gun based impact loading has been successfully used to generate impulsive loading through water [1-6]. A major of aspect of marine composite structures that has not been thoroughly investigated is the response of cylindrical composite structures to blast loads.

The objective of the present work is to characterize the dynamic deformations and damage response of curved sandwich composites with different core densities but similar total masses subjected to high intensity underwater impulsive loads. The analysis focuses on the effect of varying structural attributes and material properties on load-carrying capacity, deflection, energy dissipation and damage. This is a combined experimental and computational study. The USLS consists of a projectile impact based impulsive loading system, a water chamber, a target holder and a safety enclosure. A complementary 3D numerical model is used to investigate the various aspects of mechanical response of cylindrical structures. The targets can be subjected to a range of impulsive loads with durations between 300 and 1000 μs, and peak pressures up to 100 MPa. In-situ measurements are carried out using high-speed digital imaging and force transducers which provides an opportunity to evaluate the blast resistance of cylindrical composites during an underwater detonation event. The analysis uses metrics such as out-of-plane deflection and energy dissipation through different deformation modes to quantify blast mitigation capabilities of each configuration. The results are presented in normalized forms to identify underlying trends in material and structural response and to enable structural design based on operational requirements. The major fracture mechanisms include interlaminar delamination between composite plies with different fiber orientations, intralaminar cracking, core cracking and core-face debonding.

2. Experimental apparatus

Planar underwater impulses are generated using a novel experimental setup called the Underwater Shock Loading Simulator (USLS). The USLS consists of a projectile impact based impulsive loading mechanism and clamped and simply supported boundary conditions. The cylindrical structure is supported on a steel flange because this loading condition closely resembles that found in a naval structure. A force transducer is mounted on the flange to measure impulses transmitted in each case. The location of the failure modes in this configuration allows accurate time resolved measurements using high-speed digital imaging. Specifically, high-speed digital imaging and digital image correlation enables the study of deflection, face wrinkling, core face debonding, core compression, core shear cracking and rupture and their dependence on load intensity and core characteristics. This experimental setup is shown in Fig. 1. The USLS can generate impulsive loads with peak pressures within the range 40-250 MPa, which resemble those created by an underwater explosion. Fig. 2 shows the pressure histories of underwater impulses corresponding to different projectile velocities.

3. Materials

The composite specimens are constructed with glass fiber reinforced plastic with two winding angles [45^o] and [-45^o]. The wall thickness of monolithic cylindrical specimens is 5.5 mm. For the sandwich structure, the outer face is 3.5 mm thick, the inner face is 2.5 mm thick and the sandwich core is 10 mm thick. The core material is Divinycell HP100 PVC foam manufactured by DIAB Inc. [7]. Fig. 3 shows the different components of a filament wound composite cylinder. The sandwich structure is manufactured by cutting the PVC foam into the required segments, inserting into concentric composite cylinders and impregnating the assembly with polyester resin. The inside surfaces of the cylindrical specimens are painted with an enamel spray to improve reflectivity for high-speed photography.

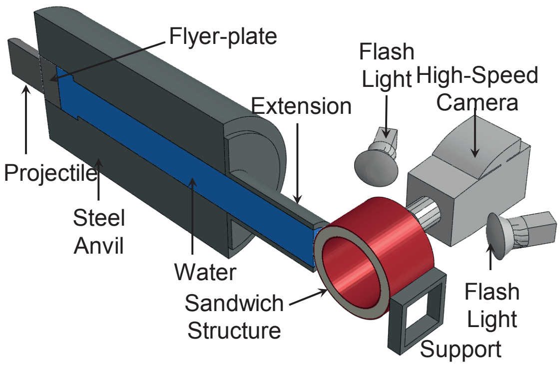

Fig. 1. Sectional view of Underwater Shock Loading Simulator (USLS) showing the setup for high speed digital imaging of impulsively loaded cylindrical structures.

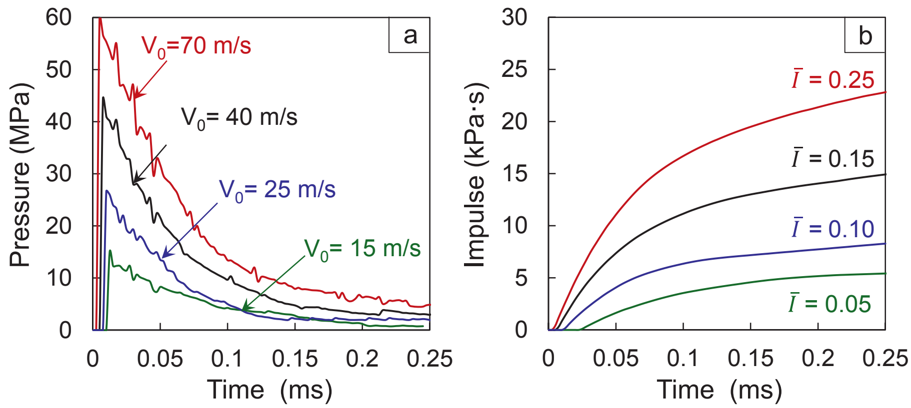

Fig. 2. Experimentally measured pressure histories in the water chamber for four different projectile velocities and impulse magnitudes. Also shown are the corresponding normalized incident impulses $\left(\bar{I} = \int p(t)\,dt \big/ \rho_w c_w \sqrt{A}\,,\right)$.

4. Numerical framework

4.1. Modeling of water-structure interaction

In Lagrangian analyses, nodes are fixed within the material and the nodes displace and corresponding elements deform as the material deforms. Since Lagrangian elements are always 100% full of a single material, the material boundary coincides with the element boundary. By contrast, Eulerian analyses consist of nodes that are fixed in space and the material flows through elements that do not experience deformation. Eulerian elements may also be partially or completely void, allowing material to flow into empty space, capturing a crucial aspect of analyses involving liquids being subjected to high pressures. The Eulerian material can interact with Lagrangian elements through Eulerian-Lagrangian contact to allow fully coupled multi-physics simulations like fluid-structure interaction. In this analysis, a Coupled Eulerian Lagrangian (CEL) framework is employed because it captures the extreme deformation in water during the impact event. In addition to simulating the blast wave propagation in the USLS, the Eulerian formulation accurately captures the exponentially decaying pressure waves and resulting cavitation at the fluid structure interface. The interaction between the water and structure is effected by tying the nodes in the water to the corresponding nodes of the structure, thereby ensuring continuity of displacements. The response of water in the Eulerian domain is described by the Mie-Grüneisen equation of state such that

$$p = \frac{\rho_0 c_0^2 \eta}{(1 - s\,\eta)^2}\left(1 - \frac{\Gamma_0 \eta}{2}\right) + \Gamma_0 \rho_0 E_m, \tag{0}$$

where p is the pressure, c_0 is the speed of sound, ρ_0 is the initial density, E_m is internal energy per unit mass, Γ_0 is Grüneisen's Gamma at a reference state, $s = dU_s / dU_p$ is the Hugoniot slope coefficient, U_s is the shock wave velocity, and Leggsss86 is the particle velocity which is related to U_s through a linear Hugoniot relation $U_S = c_0 + sU_p$. The parameters for the Mie- Grüneisen equation of state are listed in **Errore. L'origine riferimento non è stata trovata.**. The space enclosed by the anvil shown in **Errore. L'origine riferimento non è stata trovata.** is prescribed the properties of water while the space that is outside the anvil is kept as a "void", allowing water to flow into it as a result of high intensity pressure wave impinging on the target. This has the effect of instantaneously relieving the pressure in the water-chamber in a manner consistent with experimental observations.

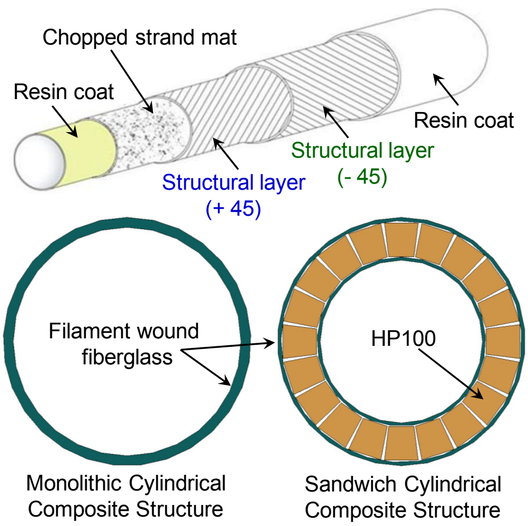

Fig. 3. Components of filament-wound, cylindrical fiberglass structure with [45°]/[-45°] orientation.

4.2. Constitutive behavior for PVC foams

The high strain rate behavior of cellular foams has been investigated using Split Hopkinson Pressure Bar apparatuses. These experiments show that PVC foams exhibit mild strain rate sensitivity in the strain rate range of &&= 10^{-2} to 10^{3} s^{-1} and negligible strain rate sensitivity in the strain rate range of &&= 10^{-4} to 10^{-2} s^{-1}. The primary mechanism for energy absorption in foam cores is local wall collapse and stress-saturated volumetric compression. The Deshpande and Fleck crushable foam plasticity model [8] is used to describe the constitutive behavior of PVC foams. The PVC foam core used in the experiments is DIAB Divinycell HP [7] with densities of 60, 100, 130, 200 and 250 kg/m^3.

4.3. Constitutive and damage models for composite laminates

A finite-deformation framework is adopted to account for large deformations in the composite. Linear orthotropic elastic constitutive behavior is assumed. Damage initiation and failure of each composite ply are captured with

Hashin's damage model [9, 10]. This is a homogenized model so that individual fibers and fiber-matrix interfaces are not modeled explicitly. Rather, the model provides a phenomenological representation of the different damage modes in composite structures. This framework incorporates four damage mechanisms: (1) matrix damage in tension, (2) matrix damage in compression, (3) fiber damage in tension, and (4) fiber damage in compression.

4.4. Cohesive finite element framework

Cohesive elements are specified between at the interfaces between individual laminas in the composite structure as well as the interfaces between the core and facesheets. The cohesive elements allow for damage initiation and development. A bilinear traction-separation law is adopted to govern the behavior of the cohesive elements. Once damage is initiated in a cohesive element, the interface follows the mixed-mode fracture criterion. The damage is governed by tractions and critical fracture energies in the normal and shear directions. The traction-separation stiffness for cohesive elements along interfaces between the phases and within the bulk phases is a factor of 10^3 times the stiffness of the corresponding bulk elements. This choice has two benefits: (1) artificial softening of the model is avoided; and (2) the work of separation associated with the linear-elastic portion of the cohesive behavior is minimized, ensuring that the bulk of the work is in the fracture energy.

4.5. Water-tank, projectile, piston, platens and supports

The water-tank and supports are made of stainless steel and the piston, projectile and platens are made of aluminum. A Lagrangian formulation is adopted for these components and linear elastic constitutive behavior is assumed. Non-penetrating, penalty contact interactions are specified between each of the components. The compressive strains and corresponding transmitted impulses can be used to accurately evaluate the performance and blast resistance of each structural foam. This analysis is carried out in such a way that the compressive behavior of PVC foams is correlated with the collapse and failure of sandwich structures. To this end, quantitative loading-structure-performance relations are developed using experimental and computational data.

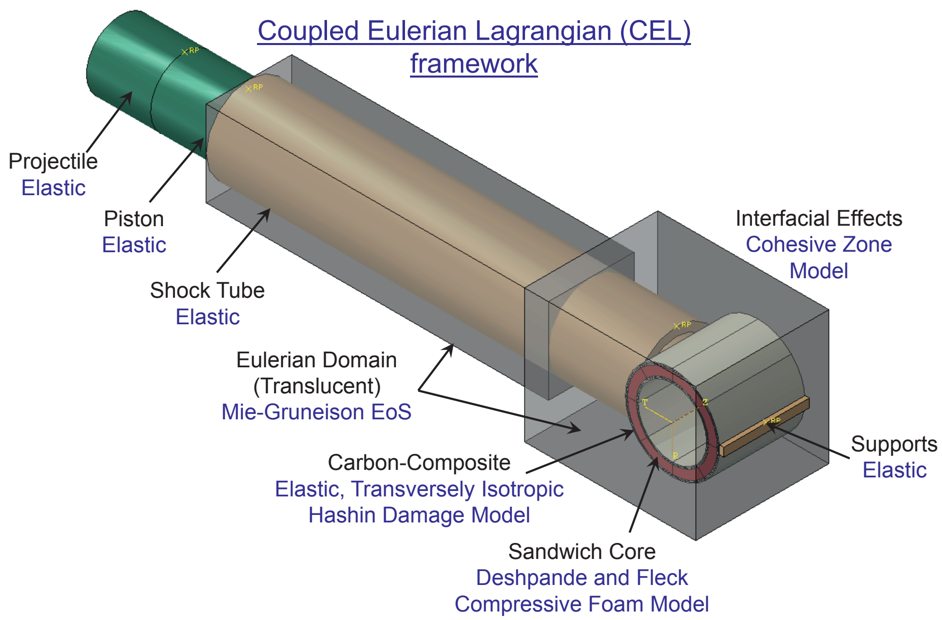

Fig. 4. Coupled Eulerian-Lagrangian computational framework with different constitutive behaviors specified for different components.

5. Results and discussion

The time histories of energy dissipation in the monolithic structure are shown in **Errore. L'origine riferimento non è stata trovata.**(a-c) for $\bar{I} = 0.25$. Compression in the bulk composite is the primary dissipation mechanism in the earlier stages of deformation, as the matrix absorbs the input energy and accommodates the imposed deformation. Accordingly, delamination initiates soon after the onset of the impulsive load as the interlaminar interfaces fail due to shear stresses. The failed surfaces interact with each other causing friction. The frictional dissipation in the structure is initially significantly lower than fracture work but as the fracture surfaces interact with each other frictional dissipation surpasses both strain energy as well as fracture work. **Errore. L'origine riferimento non è stata trovata.**(b) shows the energy dissipated due to the creation of new crack surfaces while **Errore. L'origine riferimento non è stata trovata.**(c) shows energy dissipation due to friction between failed surfaces.

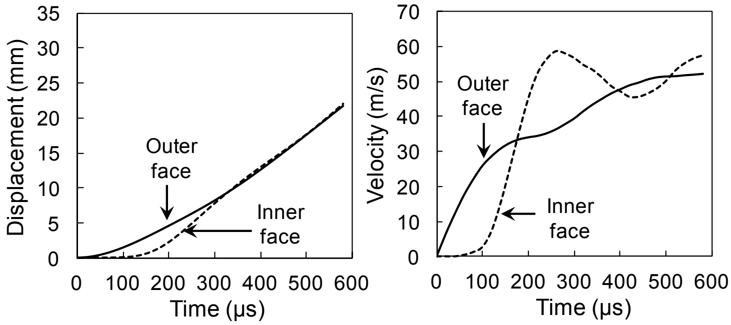

Fig. 5. Numerically calculated displacement and velocity as functions of time for the inner and outer face of a cylindrical sandwich composite structure subjected to an impulsive load corresponding to V_0 = 50 m/s.

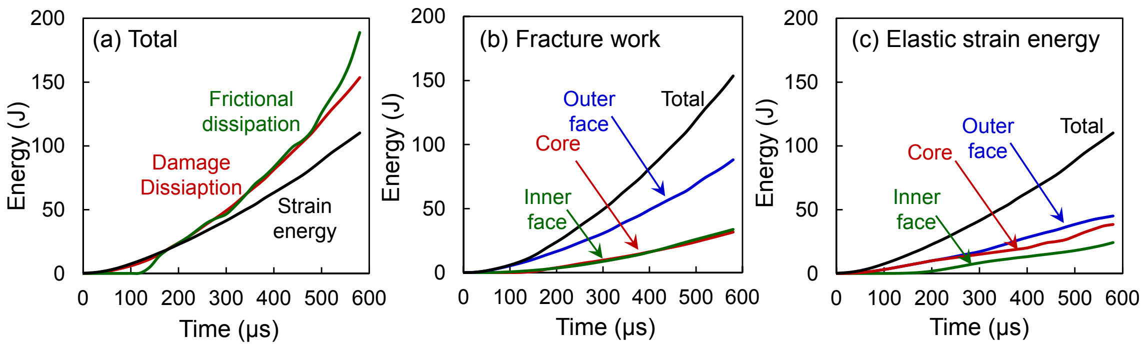

Fig. 6. Energy dissipated in a cylindrical sandwich composite structure subjected to underwater impulsive loading.

Fig. 5 shows the time histories of displacement and velocity for the inner and outer face of a cylindrical sandwich composite structure subjected to an impulsive load corresponding $\bar{I} = 0.25$. Initially, the core is compressed and the outer face travels faster than the inner face. As deformation progresses and the load is transmitted to the inner face, the inner face acquires velocity and travels in a direction opposite to the impulsive loading direction. The evolution of elastic strain energy, fracture work and frictional dissipation as functions of time is shown in Fig. 6. The energy expenditure in the entire structure is shown in Fig. 6(a). Elastic strain energy is higher in the initial stages of deformation. As damage initiates in the form of delamination, intralaminar cracking and core cracking, the magnitude of energy dissipated in formation of cracks increases monotonically. With an increase in overall fracture, the interactions between fractured surfaces also increases leading to high frictional dissipation. The fracture work and frictional dissipation both surpass the elastic strain energy. Fig. 6(b) shows the energy dissipated due to the creation of crack surfaces. The outer face, which is in close proximity to the impulsive load, undergoes the highest fracture work while the core and inner face exhibit similar energy dissipation characteristics. Fig. 7 shows the time histories of energy spent in creating cracks in different components of the sandwich structure. Clearly, damage initiation and growth is affected by material orientation, interfacial effects and core cracking.

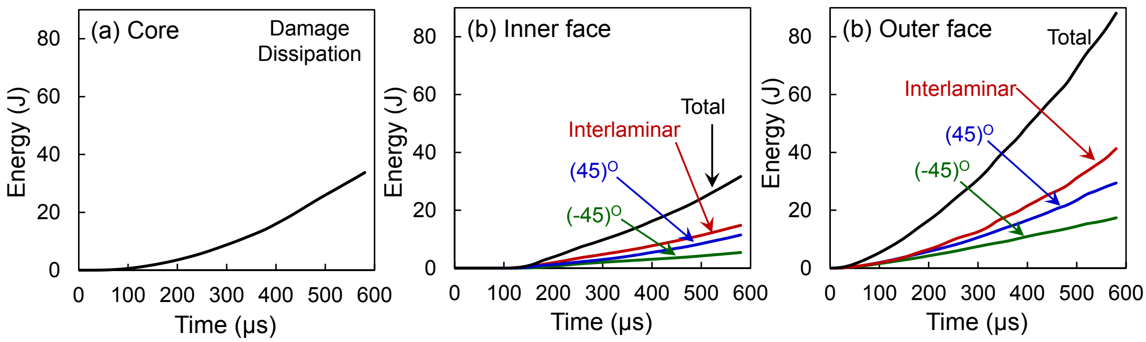

Fig. 7. Fracture work in different components of a cylindrical sandwich composite structure subjected to underwater impulsive loading.

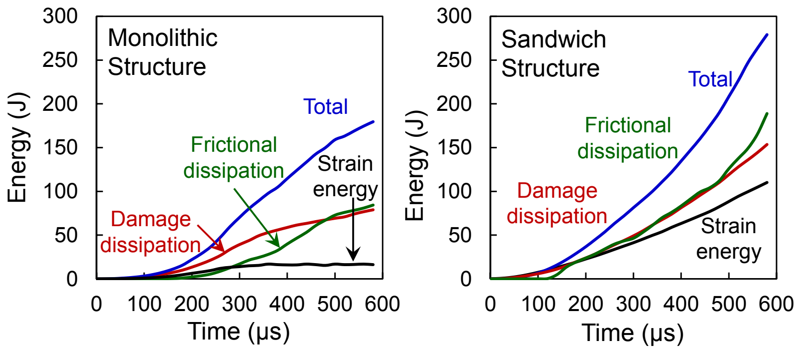

Fig. 8. Comparison of total energy dissipation in monolithic and sandwich structures subjected to similar impulsive loads.

6. Concluding remarks

The response of filament-wound cylindrical composite structures is investigated numerically and experimentally. The materials of choice are glass-fiber reinforced polymer and structural PVC foam, commonly found in marine construction. Underwater impulsive loading experiments are conducted at a fixed stand-off distance with impulsive loads similar to those observed in an underwater blast. Fluid-structure interaction is captured using an equation of state for water. A novel multiphysics computational framework is implemented to accurately track the various deformation mechanisms in composite structures. This framework is able to accurately depict the role of fluid-structure interaction during underwater explosions, and interlaminar delamination and cracking, fiber and matrix damage, intralaminar and translaminar cracking and friction.

Experiments show that monolithic and sandwich composite structures exhibit multiple competing failure modes include core compression, delamination, core-face debonding, translaminar cracking, matrix and fiber rupture. Maximum core compression was observed on the side nearest to the blast loading indicating that the outer face deformed significantly into the core before recovering. For similar total mass, the sandwich structure provided considerably superior blast mitigation as compared to the monolithic structure. Overall, filament wound cylindrical structures exhibited good resiliency under blast loading. While the monolithic structure showed signs of severe internal damage and warpage, the sandwich structure was relatively unwarped and recovered most of the original geometry.

Numerical simulations carried out in this analysis provide an insight into the deformation mechanisms and energy dissipation in the composite structures. Simulations show that interlaminar delamination is an important damage mechanism. Delamination contributes to only 20% of the overall fracture work and ~ 5% of total energy dissipation and it is the driving force for other failure modes in the composite. Delamination precipitates the formation of intralaminar cracks which lead to catastrophic failure and rupture. Additionally, interlaminar cracks span across large sections of the composite structure while fiber and matrix damage is restricted to small regions close to the loading area. Simulations reveal that friction between cracked surfaces is major source of energy expenditure and is comparable in magnitude to fracture work and strain energy. Cracking and friction at the core face inteface is found to be negligible in all cases. This can be attributed to the presence of the low density foam core which does not provide a significant resistance to shear deformation. Computations reveal that cylindrical sandwich structures outperform monolithic structures significantly. The sandwich core helps mitigate the effects of high pressures on the cylindrical structure. Fig. 8 shows a comparison of energy dissipation in the form of fracture, friction and elastic strain. Results indicate that for a similar applied impulse, the sandwich structure dissipates almost twice as much energy as the monolithic structure. This is primarily because of the presence of a compressible foam core and a thinner outer face which contribute to higher elastic strain and fracture work respectively. The numerical capability can be utilized to design and optimize curved fiber composite structures subjected to side-loading in navy vessels.

Acknowledgements

The authors gratefully acknowledge support by the Office of Naval Research (program manager: Dr. Yapa D. S. Rajapakse).

References

1. Espinosa, H.D., S. Lee, and N. Moldovan, *A novel fluid structure interaction experiment to investigate deformation of structural elements subjected to impulsive loading.* Experimental Mechanics, 2006. **46**(6): p. 805-824.
2. Latourte, F., et al., *Failure mechanisms in composite panels subjected to underwater impulsive loads.* Journal of the Mechanics and Physics of Solids, 2011. **59**(8): p. 1623-1646.
3. McShane, G.J., et al., *Dynamic rupture of polymer-metal bilayer plates.* International Journal of Solids and Structures, 2008. **45**(16): p. 4407-4426.
4. Avachat, S. and M. Zhou, *Effect of core density on deformation and failure in sandwich composites subjected to underwater impulsive loads.* The International Journal of Multiphysics 2012. **Volume 6**(Number 3).
5. Avachat, S. and M. Zhou, *Effect of Facesheet Thickness on Dynamic Response of Composite Sandwich Plates to Underwater Impulsive Loading.* Experimental Mechanics, 2012. **52**(1): p. 83-93.
6. Dannemann, K.A., V.B. Chalivendra, and B. Song, *Dynamic Behavior of Materials.* Experimental Mechanics, 2012. **52**(2): p. 117-118.
7. DIAB Inc., S.D., DeSoto, Texas 75115, USA.
8. Deshpande, V.S. and N.A. Fleck, *Multi-axial yield behaviour of polymer foams.* Acta Materialia, 2001. **49**(10): p. 1859-1866.
9. Hashin, Z., *Failure Criteria for Unidirectional Fiber Composites.* Journal of Applied Mechanics-Transactions of the Asme, 1980. **47**(2): p. 329-334.
10. Hibbit, Karlsson, and Sorensen, *Abaqus/Explicit User's Manual, Version 6.9.* 2009.